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# Experimental Investigation of Combustion and Emission Characteristics for Internal Combustion Rankine Cycle Engine under different Water Injection Laws

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**Abstract**

This paper discusses a novel oxyfuel combustion method named internal combustion rankine cycle (ICRC) used in reciprocating engines. Water is heated up through heat exchanger by exhaust gas and engine coolant, and then injected into the cylinder during the combustion to control the oxyfuel combustion temperature and reaction rate. Moreover, evaporation of the water mist increases the mass of working fluid so indicated thermal efficiency of the cycle is enhanced. This study investigates combustion and emission characteristics of ICRC engine under different water injection laws. The results show that indicated work and thermal efficiency increases significantly due to water injection process. The properly increase of injection duration and pressure improve IMEP (Indicated mean effective pressure) and thermal efficiency. Engine stability becomes better under lower water injection pressure and less injection duration. Less water injection duration and better injection atomization causes lower HC emissions, while NOx emissions stay under low level.


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Keywords: *Oxyfuel combustion, waste heat recovery, water direct injection, IC engine, Emission*

## 1. Introduction

As one of promising $CO_2$ reduction technologies, Carbon capture using oxyfuel combustion method can control and avoid not only $CO_2$ emissions but also NOx emissions significantly. The use of the oxyfuel is wide in the area of power generation domain. CES (Clean Energy System) merges oxyfuel combustion and water injection [1]. In this system, water is injected into the gas generator to increase the mass of working fluid. This type of oxyfuel combustion power-plant cycles are called internal combustion Rankine cycles (ICRCs). Basic thermo efficiencies for the ICRC steam turbine cycle can reach 65% or more. [1]. Water injection at ambient temperature is also employed in internal combustion engines, such

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as knock suppressant [2], an internal coolant [3], and a way to reduce NOx emissions [4] because it can reduce flame propagation and in-cylinder temperature.
The Application of ICRC in reciprocating engines was studied [5]. The schematic of the ICRC system can be found in [7]. Oxygen mixed with EGR (Exhaust Gas Recycling) is inhaled into cylinder during intake stroke. Water is heated by exhaust gas and engine coolant, and directly injected into the cylinder during the combustion. Since combustion with higher oxygen concentration is more intense, more water can be added as working fluid with less negative impact. The exhaust gas is mixture of $CO_2$ and water vapor, which can be easily separated through condensation process at relatively low price. In this way, almost pure $CO_2$ can be captured and stored in a tank. Hence, a high thermo efficiency combustion cycle with ultra-low emission is achieved. The feasibility and efficiency of the cycle were investigated [5-7]. Ideal thermal efficiency of the cycle could reach to 56% and even more. The preliminary experiment studies by authors showed that injected water could increase the mass of the working fluid and enhance the indicted work of engine [7-8].
In the present study, a self-designed ICRC prototype engine test bench was built. To simplify experiments at the beginning of the study, $O_2/CO_2$ mixture gas simulated the intake with EGR. Likewise, self-designed water injection supply system was employed to control water injection temperature and pressure accurately. Combustion and emission of ICRC under different water injection laws were investigated.

## 2. Experimental apparatus and procedure

The schematic diagram of test bench is shown in Figure 1. The engine was a retrofitted, single-cylinder, air-cooled SI engine (bore x stroke/56.5mm x 49.5mm; displacement/124cm$^3$) with propane fuel (intake manifold injection). Water was directly injected into the cylinder by a solenoid diesel injector. The details of experimental setups can be found in [7].

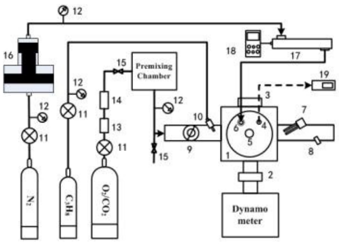


**Figure 1.** Schematic of the test bench dedicated to ICRC engine

**Table 1.** Operating conditions

| | |
|---|---|
| Speed (r/min) | 2400 |
| O2 volume fraction (%) | 50 |
| Ignition timing (°CA BTDC) | 30 |
| Water Injection timing (°CA BTDC) | 0 |
| Water Injection temperature (°C) | 120 |
| Throttle position (%) | 15 |

100 cycles were collected for each condition containing 50 continuous water cycles and 50 no water injection cycles (dry cycles). Average value of pressure was employed. The operating conditions are listed in table 1. Water was injected into the cylinder with different pressures ($P_{inj}$=20MPa~24MPa) and different injection durations ($t_{inj}$=0ms~1ms). Error analysis of the derived quantities can be found in [7].

## 3. Experimental results and analysis

Figure 2 shows the in-cylinder pressure under different water injection durations ($P_{inj}$ =22MPa). The combustion phasing is retarded in water injection cycles. The peak in-cylinder pressure ($P_{max}$) reduces and the combustion phasing is retarded with the increase of $t_{inj}$. Besides, the in-cylinder pressures of water cycles in the work stroke are higher than the pressure of dry cycles, and the increment of pressure increases when $t_{inj}$ is increased. The reason is that the injected water increases the mass of working fluid. It is noteworthy that the in-cylinder pressure of the water injection cycle from combustion start to TDC (Top Dead Center) is lower than pressure of the dry cycle for all cases, which is because the residual water from last cycle results moderates the combustion process of the next cycle.

Figure 3 shows the comparisons of $P_{max}$ and $W_i$ under various fuel mass ($m_{fuel}$=5.2, 5.8mg) with different $t_{inj}$. $P_{max}$ and $W_i$ increase with the increase of fuel mass. $P_{max}$ increases compared with the dry cycles when $t_{inj}$ is 0.25ms, because that the supplement of rapider evaporating water vapor to working fluid causes higher $P_{max}$. However, when $t_{inj}$ increases to 0.4ms and 1ms, excess water is injected into the cylinder during the combustion. Water mist has more negative effect on combustion, which leads to the reduction of $P_{max}$. The reduction is more obvious with less fuel mass ($m_{fuel}$=5.2mg) due to the lower in-cylinder temperature. It is also seen in the Figure 3 that $W_i$ ($m_{fuel}$=5.8mg) increases with increase of $t_{inj}$ while $P_{max}$ firstly increase and then reduce. The properly increase of $t_{inj}$ results in lower $P_{max}$ but more working fluid mass, thus increases expansion pressure and improves IMEP. The increment of $W_i$ reaches to maximum (21%) when $t_{inj}$ is 0.4ms. However, $W_i$ reduces while $t_{inj}$ increases to 1ms, because excessive reduction of $P_{max}$ interferes with the increase of $W_i$. The same trend is also found when fuel mass is 5.2mg.

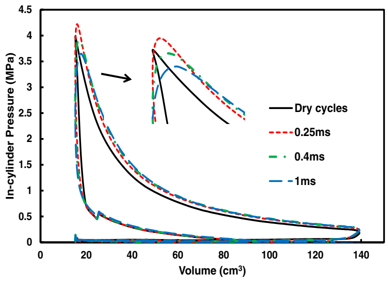


**Figure 2.** In-cylinder pressure under different water injection durations

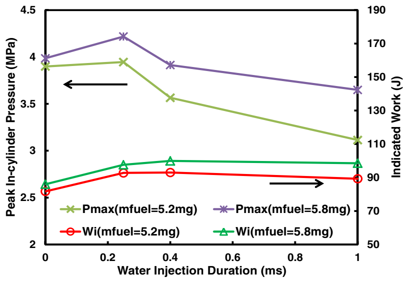


**Figure 3.** Peak in-cylinder pressure and indicated work under various fuel mass with different water injection durations

Figure 4 illustrates the in-cylinder pressure with different $P_{inj}$ ($t_{inj}$ =0.4ms). Higher $P_{inj}$ is propitious to higher $P_{max}$ while more $t_{inj}$ makes against higher $P_{max}$, although both two methods can add the mass of water injection. The reason is that higher $P_{inj}$ means better atomization and evaporation, and that adds the mass of water vapor and reduces negative effects of water mist on combustion at the same time. $P_{max}$ reaches 4.17MPa when $P_{inj}$ is 24MPa.

Figure 5 shows the relationship between peak in-cylinder pressure and indicated work under different water injection pressures. It is shown that both $P_{max}$ and $W_i$ increase with the increase of $P_{inj}$. The indicated work increases by 24% and indicated thermal efficiency (ITE) increases by 6% compared to the work of the dry cycles when $P_{inj}$ is 24MPa and $m_{fuel}$ is 5.8mg.

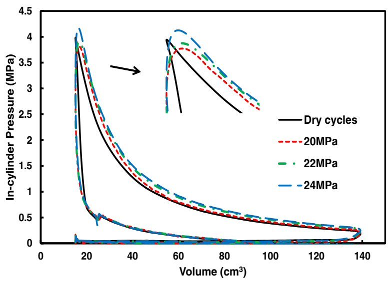


**Figure 4.** In-cylinder pressure under different water injection pressures

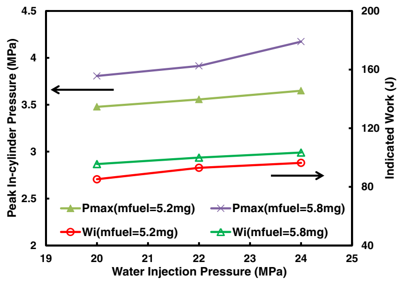


**Figure 5.** Peak in-cylinder pressure and indicated work under various fuel mass with different water injection pressures

The COV (Coefficient of Variation) value of IMEP ($COV_{IMEP}$) is commonly used to determine cyclic dispersions and variations of combustion. It is shown in Figure 6 that the engine cyclic variation of water cycles is more obvious than the cyclic variation of dry cycles. Besides, more $t_{inj}$ and higher $P_{inj}$ cause the increase of $COV_{IMEP}$, which means increasing engine cyclic variation and bad combustion stability.

The details of emission measurement instruments and data acquisitions are introduced in [8]. NOx exists due to the remaining $N_2$ of industrial $O_2$ and $CO_2$ tank for the experiment. Figure 7 shows the HC and

NOx emissions of ICRC engine under different water injection laws. HC emission increases with the increase of $t_{inj}$. HC emission reduces when $P_{inj}$ increases from 20MPa to 22MPa, because better atomization of water spray speeds up evaporation of water under higher $P_{inj}$, which reduces the negative impact of water mist to combustion. Atomization is improved when $P_{inj}$ increase from 22MPa to 24MPa, but HC emission does not reduce accordingly. Because more water is injected into cylinder per unit time and it has a negative impact to combustion. In contrast, NOx emission is very low because injected water reduces in-cylinder temperature.

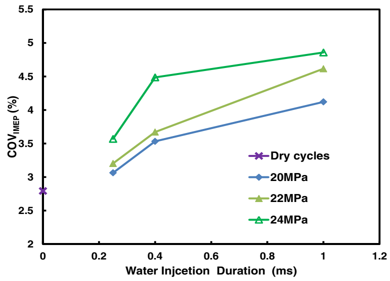


**Figure 6.** Effect of water injection laws on COV of IMEP (mfuel =5.2mg)

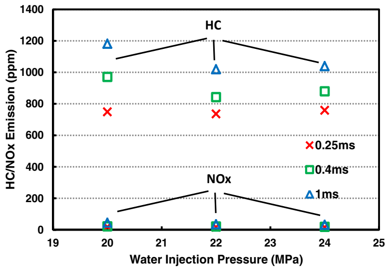


**Figure 7.** Emissions of ICRC engine under different water injection laws

## 4. Conclusions

1. The injected water increases the mass of the working fluid during work stroke. Both indicated work and thermal efficiency increase significantly compared with the dry cycles due to water injection process. $W_i$ and ITE is increased by 24% and 6% separately when $P_{inj}$ is 24MPa and $m_{fuel}$ is 5.8mg.
2. The properly increase of water injection duration and pressure can increase expansion pressure and improves IMEP. Higher water injection pressure is propitious to higher peak in-cylinder pressure while more water injection duration makes against higher peak in-cylinder pressure, although both two methods can add the mass of water injection. Engine stability becomes better when less water is injected.
3. Less water injection duration and better injection atomization causes lower HC emissions, while NOx emissions stay under low level.

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## References

[1] Bilger, R. W., “Zero release combustion technologies and the oxygen economy,” Fifth International Conference on Technologies and Combustion for a Clean Environment,” Portugal, 1999, 1039-1046.

[2] Lanzafame R, “Water injection effects in a single-cylinder CFR engine,” SAE Paper 1999-01-0568, 1999.

[3] R.B. Melton Jr., S.J. Lestz, R.D. Quillian Jr, “Direct water injection cooling for military engines and effects on the diesel cycle,” Fifteenth Symposium (International) on Combustion: Vol 15(1), 1975, 1389–1399.

[4] V. Subramanian, J.M. Mallikarjuna, A. Ramesh, “Effect of water injection and spark timing on the nitric oxide emission and combustion parameters of a hydrogen fuelled spark ignition engine,” International Journal of Hydrogen Energy: 32 (2007),1159 – 1173.

[5] Bilger R W., Zhijun Wu, “Carbon Capture for Automobiles Using Internal Combustion Rankine Cycle Engines,” Journal of Engineering for Gas Turbines and Power. 01/2009, 131(3) .

[6] Alberto Borettia, Azmi Osmanc, Ishak Aris, “Direct injection of hydrogen, oxygen and water in a novel two stroke engine”, International Journal of Hydrogen Energy. 36(2011), 10100-6.

[7] Zhijun Wu, Xiao Yu, Lezhong Fu et al, “A high efficiency oxyfuel internal combustion engine cycle with water direct injection for waste heat recovery,” Energy.70(2014), 110–120.

[8] Yu, X., Wu, Z., Wang, C., Deng, J. et al, “Study of the combustion and emission characteristics of a quasi ICRC Engine under different engine loads,” SAE Technical Paper 2014-01-1202, 2014.